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The Pebble Bed Modular Reactor

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CONTENT LINKS:

INTRODUCTION:

The development of the nuclear power industry has been nearly stagnant in the past few decades. In fact there have been no new nuclear power plant construction in the United States since the late 1970s [1]. What many thought was a promising technology during the "Cold War" days of this nation; they now frown upon, despite the fact that nuclear power currently provides the world with 17% of its energy needs [1]. Nuclear technology's lack of popularity is not difficult to understand since the fear of it has been promoted by the entertainment industry, news media, and extremists. There is public fear because movies portray radiation as the cause of every biological mutation and now, terrorist threats against nuclear installations have been hypothesized. Also, the lack of understanding of nuclear science has kept news media and extremists on the offensive. The accidents at Three Mile Island (TMI) and Chernobyl were real and their effects were dangerous and, in the latter case, lethal. However, many prefer to give up the technology rather than learn from these mistakes.

Recently, there has been a resurgence of interest in nuclear power development by several governments, despite the resistance. The value of nuclear power as an alternative fuel source is still present and public fears have only served to make the process of obtaining approval more difficult. This resurgence is due to the real threat that global warming, caused by the burning of fossil fuels, is destroying the environment. Moreover, these limited resources are quickly being depleted because of their increased usage from a growing population. The estimation is that developing countries will expand their energy consumption to 3.9 times that of today by the mid-21st century and global consumption is expected to grow by 2.2 times [1]. Development has been slow in the United States since deregulation of the power industry has forced companies to look for short term return, inexpensive solutions to our energy needs rather than investment in long term return, expensive solutions. Short term solutions, such as the burning of natural gas in combined cycle gas turbines (CCGT), have been the most cost effective but remain resource limited [1]. Therefore, a few companies and universities, subsidized by governments, are examining new ways to provide nuclear power. An acceptable nuclear power solution for energy producers and consumers would depend upon safety and cost effectiveness. Many solutions have been proposed including the retrofit of our current light water reactors (LWR). At present, it seems the most popular solution is a High Temperature Gas Cooled Reactor (HTGR) called the Pebble Bed Modular Reactor (PBMR). This web page will examine the following aspects of the PBMR:

- History of the PBMR
- Description of the PBMR
- Advantages of the PBMR
- Disadvantages of the PBMR
- Latest PBMR Developments

HISTORY:

The history of gas-cooled reactors (GCR) began in November of 1943 with the graphite-moderated, air-cooled, 3.5-MW, X-10 reactor in Oak Ridge, Tennessee [3] . Gas-cooled reactors use graphite as a moderator and a circulation of gas as a coolant. A moderator like graphite is used to slow the prompt neutrons created from the reaction such that a nuclear reaction can be sustained. Reactors used commercially in the United States are generally LWRs which use light water as a moderator and coolant. Development of the more advanced HTGRs began in the 1950s to improve upon the performance of the GCRs [3] . HTGRs use helium as a gas coolant to increase operating temperatures. Initial HTGRs were the Dragon reactor in the U.K., developed in 1959 and almost simultaneously, the Arbeitsgemeinshaft Versuchsreaktor (AVR) reactor in Germany (Figure 1). Dr Rudolf Schulten (considered "father" of the **pebble bed** concept) decided to do something different for the AVR reactor. His idea was to compact silicon carbide coated uranium granules into hard billiard-ball-like graphite spheres (pebbles) and use them as fuel for the helium cooled reactor [L3] . The first HTGR prototype in the United States was the Peach Bottom Unit 1 in the late 1960s [3]. Following the success of these reactors included construction of the Fort S. Vrain (FSV) in Colorado and the Thorium High Temperature Reactor (THTR-300) in Germany. These reactors used primary systems enclosed in prestressed concrete reactor vessels rather than steel vessels of previous designs. The FSV incorporated ceramic coated fuel particles imbedded within rods placed in large hexagonal shaped graphite elements and the THTR-300 used spherical fuel elements (**pebble bed**) [3]. These test reactors provided valuable information for future designs. They proved that the overall safety characteristics of all HTGRs are due to: the high heat capacity of the graphite core; the high temperature capability of the core components; chemical stability and inertness of the fuel, coolant, and moderator; the high retention of fission products by fuel coatings, the single phase characteristics of the helium coolant; and the negative temperature coefficient of reactivity of the core [3].

Figure 1: The AVR Reactor Plant [Ref: [L3]]

The previous evaluation HTGRs were large and had high maximum core temperatures (> 2000 degrees Celsius) [3]. The first small and modular HTGR (HTR-MODULE) was a 80 MWe reactor developed in Germany by Siemons/Interatom in the early 1980's for industrial heat. It had maximum fuel element temperatures, despite all possible accident scenarios, of less than 1,600 degrees Celsius, a temperature in which all radioactive fission products are contained within the fuel elements [3]. Because of this inherent safety, the design was soon considered for producing electricity as well. Brown, Boveri und Cie and Hochtemperatur-Reacktorbau initiated the design of the HTR-100 **pebble bed** plant with this same small modular concept in mind. The reactor core used 317,500 spherical elements where, in the equilibrium cycle, 55% of the elements were fuel and the remainder where graphite moderators [3]. The United States organization that represented utility interests in the HTGR program, Gas Cooled Reactor Associates, conducted a survey in 1983 to determine the utility nuclear generation preference for the future. The survey revealed a strong interest in an incremental power generation capability. This gave important input that lead to the subsequent selection of the modular HTGR for evaluation [3]. A similar concept of the HTR-MODULE, using prismatic fuel elements, was selected for evaluation by the U.S. nuclear program in the spring and summer of 1985, deemed the Modular HTGR (MHTGR).

More recent HTGR development and tests have been conducted by China and Japan. Japan's Atomic Energy Research Institute (JAERI) began it's construction of the HTTR reactor at research facilities in Oarai, Japan, in 1991 and achieved initial criticality in November 1998. It's helium cooled reactor comprised of hexagonal fuel elements. A major project in the Chinese National High Technology Program is the HTR-10, 10 MWt, **pebble bed** reactor at the INET research site, northwest of Beijing, China. It was completed in the fall of 2000 and achieved initial criticality in December of that year [3].

Basing their design primarily on the HTR-MODULE, the **Pebble Bed Modular Reactor** (PBMR) is being developed for commercial use by an international conglomerate of U.S. based Exelon Corporation, British Nuclear Fuels Limited, and South African based ESKOM [3]. Their initial objective is to develop a 116.3 MWe demonstration reactor and start construction in Koeberg, South Africa around mid-2005. Approval for the design will need to be granted by the South African government, which may happen late-2002 [2]. Almost in parallel in January of 1998, and without prior knowledge of the PBMR effort in South Africa, a group of MIT students began their ambitious effort of developing a conceptual design of a reactor, that is now known as the Modular Pebble Bed Reactor or (MPBR). The MPBR design is very similar to the PBMR and will theoretically generate 110 MWe or 250 MWt [4].

DESCRIPTION:

The commercial effort of the PBMR is the most publicized and information about it is readily available. A description of it would cover most aspects of the modern HTGR **pebble bed** reactors. Figure 2 [from ref. [2]] shows a cross-section of the PBMR reactor and energy convertor. Therefore, the PBMR can be separated in two distinct parts. The first part is the heat source, labeled "reactor vessel", and the second part contain the power conversion units, labeled "high-pressure turbocompressor", "low-pressure turbocompressor", and "turbine generator".

The Reactor

The nuclear reaction takes place within the "reactor vessel" which is a vertical steel pressure enclosure that is 6 meters in diameter and 20 meters high [L3]. The enclosure is lined with a layer of graphite bricks which serve as an outer reflector for the neutrons generated by the reaction and a passive heat transfer mechanism [L3]. This lining is drilled with vertical holes for insertion of the control rods. Illustrated by the red and blue pebbled granules, the inner reactor core portion consists of two zones and is 3.7 meters in diameter and 9.0 meters high. The blue, or inner zone, contains approximately 185,000 graphite spheres and the red, outer zone, contains approximately 370,000 fuel spheres. The graphite spheres serve as a moderator for the nuclear reaction. This moderator slows the prompt neutrons created from the reaction such that a nuclear reaction can be sustained. As the arrows indicate, helium flows through the fuel pebble bed and is heated to provided working fluid for the generator. The helium also naturally serves as a coolant for the reactor as well, much like water does for today's LWRs.

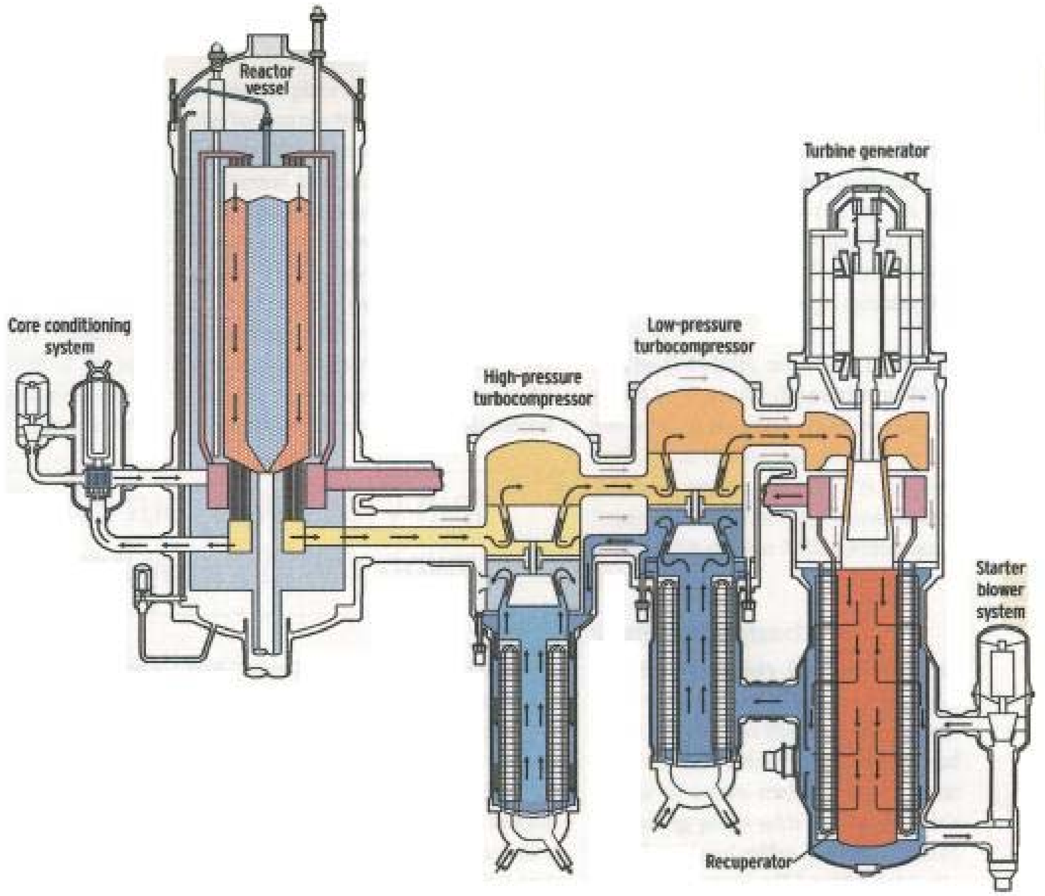

Figure 2: Pebble Bed Modular Reactor Cross Section (Ref: [2])

The Generator and Compressors

The remaining components of the reactor can best be described using the complete schematic diagram shown in Figure 3 [from ref. [L3]]. As it illustrates, helium enters the reactor at 500 degrees Celsius and at a pressure of about 8.4 MPa. It leaves the reactor at about 900 degrees Celsius and drives the high pressure turbine. The high pressure turbine will drive the return high pressure compressor. After the high pressure turbine, the helium flows through the low pressure turbine that drives the low pressure compressor. While still hot, the helium leaves the low pressure turbine and drives the power turbine to produce the electricity through the generator. The helium leaves the power turbine and is cooled in the recuperator. Return helium is then compressed back to a pressure of 8.5 MPa while it returns through the pre-cooler, low pressure compressor, inter-cooler, and high pressure compressor. The coolers increase the efficiency of the compressors since they increase the density of the helium. The helium has also been cooled back down to 500 degrees Celsius and the cycle repeats itself as it travels back to the reactor. This process is called the Brayton (gas turbine) Cycle [L3] . The advantage of this process is its high efficiency of thermal energy transfer to electrical energy. As mentioned, the efficiencies of today's LWRs are approximately 30% where the PBMR yields approximately 44% [4].

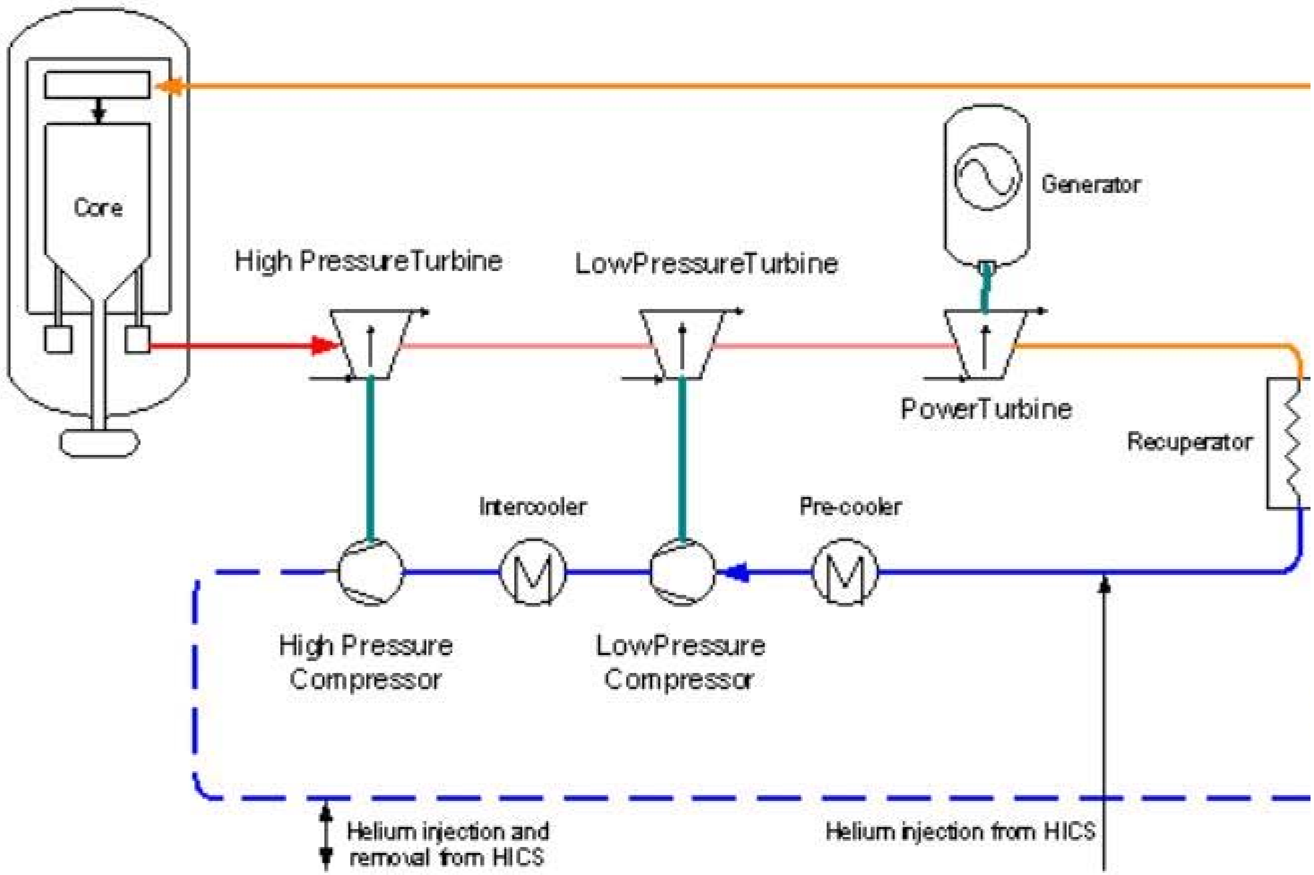

Figure 3: Pebble Bed Modular Reactor Schematic Diagram (Ref: [L3])

The Fuel Pebbles

The most unique feature of the PBMR are the 370,000 fuel pebbles or spheres that produce the nuclear reaction. An illustration of the fuel spheres is given in Figure 4 (ref. [2]). The spheres are the triple coated (TRISO) type which are similar to those used in the previous test reactor designs, THTR-300 and FSV [3]. Each 60-mm diameter, billiard ball size, sphere is coated with a 5-mm thick graphite layer that is fuel free. The graphite can withstand temperatures of 2,800 degrees Celsius which is much higher than the maximum 1,600 degrees Celsius that the reaction can produce. Within this graphite layer are approximately 15,000 coated particles that are embedded in a graphite mix. Each particle is 0.92-mm diameter, containing several layers of coatings and the 0.5-mm diameter, uranium dioxide fuel kernel. The porous carbon buffer maintains the shape of the fuel kernel as it goes through deformation caused by density change from the fission products produced. It accommodates the fuel products without over-pressurizing the particle. The remaining pyrolytic and silicon carbide coatings prevent fission products from leaving the particle thereby preventing radiation leakage during normal operation and, worst case, accident [L3]. In particular, the silicon carbide barrier is so dense that no radiological significant quantities of gaseous or metallic fission products are released from the fuel elements at temperatures of up to 1,650 degrees Celsius[L3]. The 0.5-mm diameter uranium dioxide fuel kernel contains enriched uranium to 8.0% U-235 [L1] . Natural uranium is only 0.7% U-235 enriched. U-235 is the most predominately fissionable isotope of natural uranium. During PBMR operation, new and re-used fuel spheres are replenished at the top of the reactor as used fuel spheres are removed from the bottom of the reactor. As they leave the reactor, the used fuel spheres are measured for the amount of remaining fissionable material. If they are spent, they are automatically removed from the rotation and stored in a spent fuel storage facility. A fuel sphere will cycle the reactor about 10 times before going to the storage facility. A PBMR reactor will use about 10 to 15 complete loads of spheres in its lifetime. A fuel sphere will last approximately 3 years while its in-active graphite moderator counterpart will last approximately 12 years [L3] .

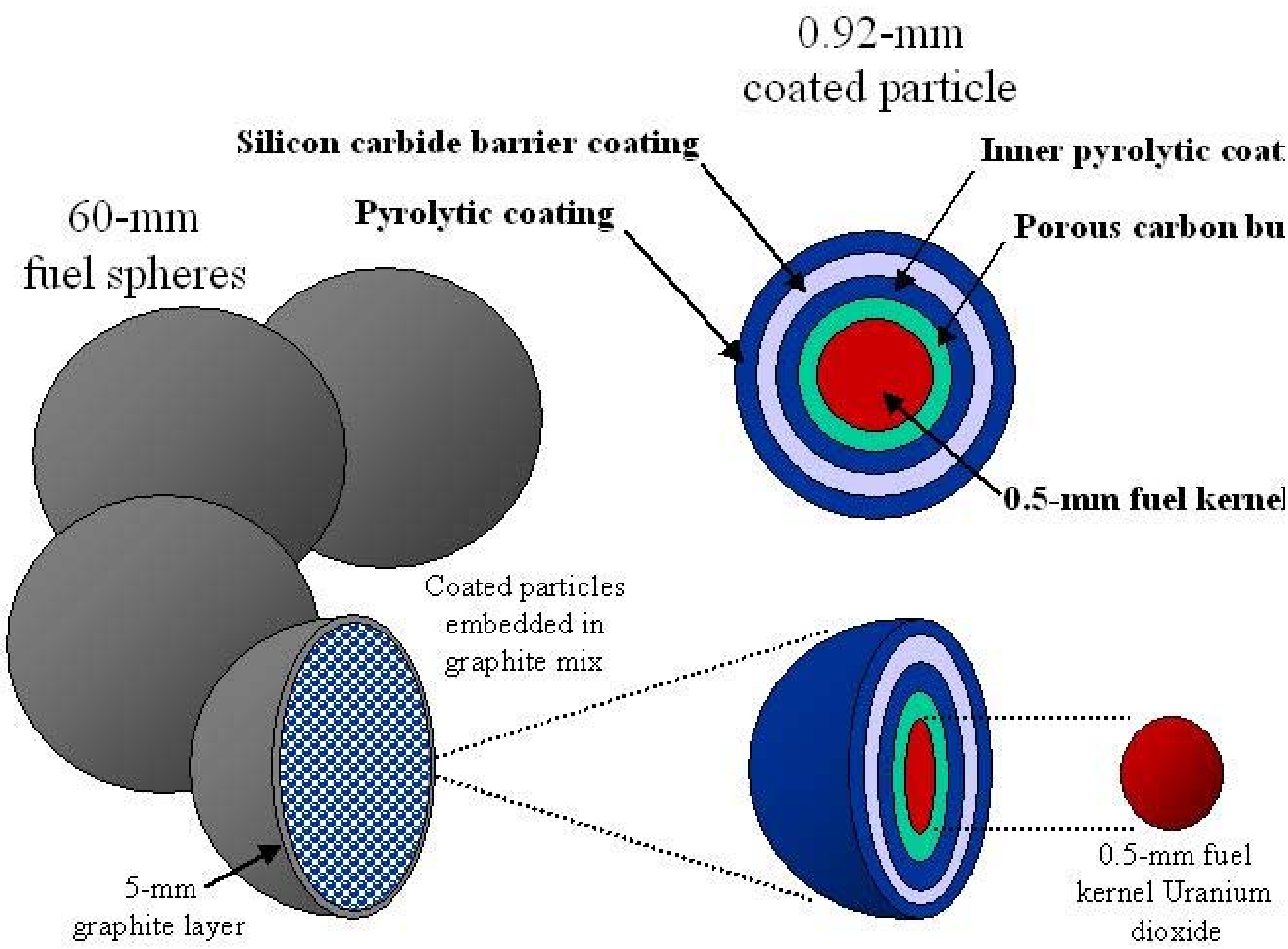

Figure 4: Pebble Bed TRISO Fuel Sphere Cross Section (Ref: [2])

From the reference data given for the fuel pebbles, a calculation is made for the average flux required for the reactor if the desired output was 116.3 MWe. Assuming a power conversion efficiency of 44%, a reactor output of 264.32 MWt would be required. The volume of the fuel is calculated using the sphere dimension, number of particles per sphere and the total number of fuel spheres in the reactor. As seen in the following, an average flux value of 6.5028 x 10^9 neutrons/cm^2*sec was calculated.

Unfortunately, none of the references seemed to give the average flux information so the result could not be verified.

$$\rho_{UO2} = 10.5 \text{ g/cm}^3 \text{ for Uranium Dioxide}$$

$$N_{U\text{-}235} = \frac{(10.5 \text{ g/cm}^3)(6.022 \text{ x } 10^{23} \text{ atoms/mole})(0.08)}{[(238)(0.92) + (235)(0.08) + 2(16)] \text{ (g/mole)}}$$

$$N_{U\text{-}235} = 1.8752 \text{ x } 10^{21} \text{ atoms/cm}^3$$

$$\sigma_f^{U\text{-}235} = 582 \text{ x } 10^{-24} \text{ cm}^2$$
$$\Sigma_f^{U\text{-}235} = \sigma_f^{U\text{-}235} N_{U\text{-}235}$$
$$\Sigma_f^{U\text{-}235} = 1.0914 \text{ cm}^{-1}$$

$$V = (4\pi /3)(0.5\text{x}10^{-1}\text{cm}/2)^3(15{,}000/\text{sphere})(370{,}000 \text{ sphere})$$
$$V = 1.1624 \text{ x } 10^9 \text{ cm}^3$$

$$E_R = (200 \text{ MeV/fission})(1.602 \text{ x } 10^{-19} \text{ J/eV})$$
$$E_R = 3.204 \text{ x } 10^{-11} \text{ J/fission}$$
$$\text{Want } P_{rx} = 264.32 \text{ MWt for } 116.3 \text{ MWe at } 44\% \text{ efficency}$$

$$P_{rx} = E_R\, \phi_{avg}\, \Sigma_f^{U\text{-}235}\, V \;\; => \;\; \boldsymbol{\phi_{avg} = 6.5028 \text{ x } 10^9 \text{ n/cm}^2 \text{ s}}$$

Note: Calculations are based only on prior knowledge from course and not from references

The PBMR Factory

The "modular" aspect of the PBMR is the reactor's small size. The reactor will produce only 116.3 MWe so about 10 of them would be needed to match the large 900 - 1000 MWe LWRs used today. A build up to 10 modular reactors is, in fact, the plan for future deployment of the PBMRs. The PBMR's size might seem more like a disadvantage; however, smaller reactors allow for better manufacturability and manageable safety features (see Advantages section). A single, modular PBMR factory is shown in Figure 5. The figure illustrates both above and below ground components of the factory. About half of the factory will be above ground and the other half below. The dimensions of the PBMR factory will be about 59 m long x 36 m wide x 57 m high[L3]. The main support structures for the reactor are the helium inventory control systems and the fuel handling and storage systems. The helium inventory control system supplies the coolant. The fuel handling and storage system performs these major tasks:

load fresh fuel pebbles, remove spent fuel pebbles, store spent fuel pebbles, recirculate good pebbles [L3].

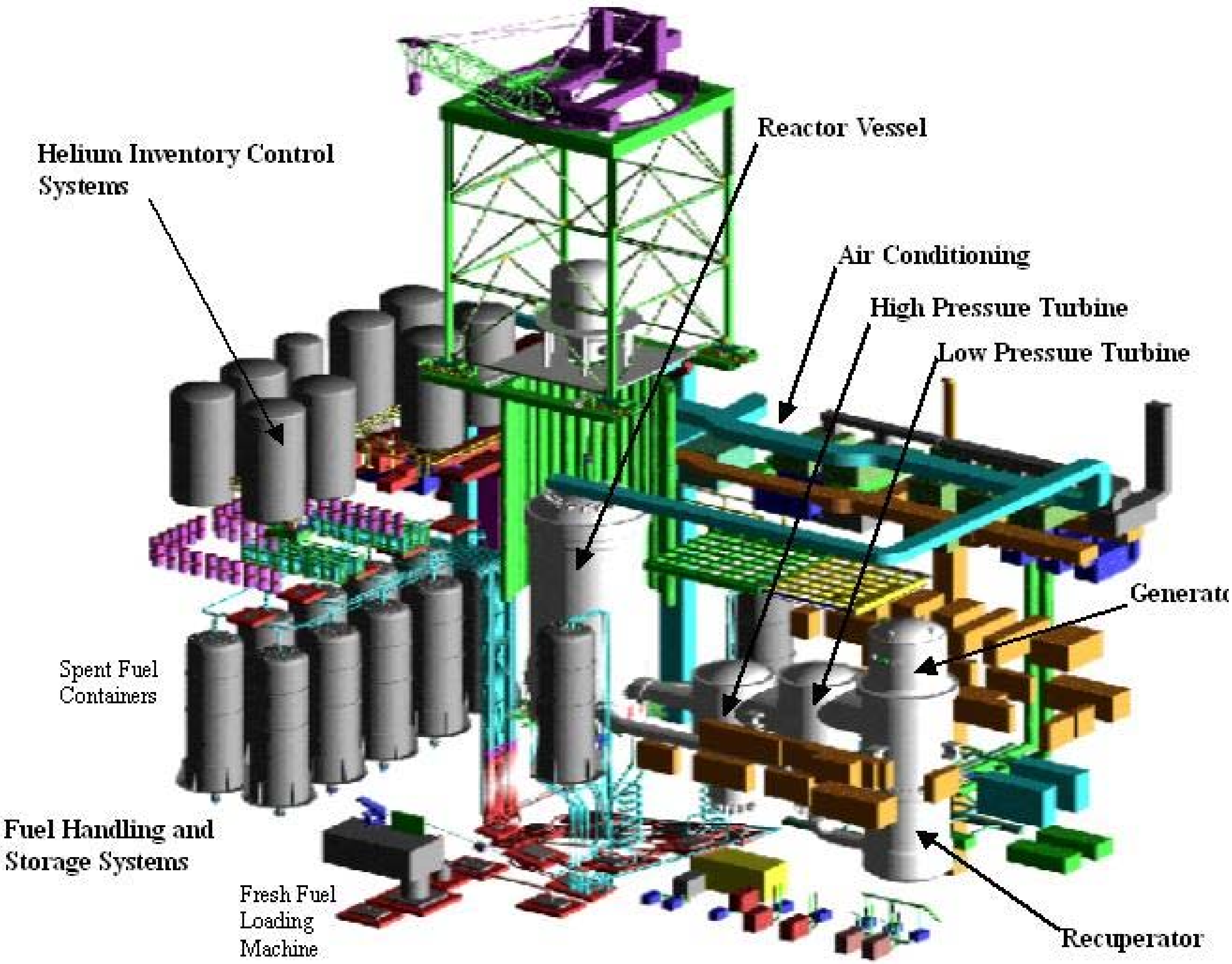

Figure 5: PBMR Reactor and Support Structures (Ref. [L3])

ADVANTAGES:

The PBMR is proposed as a solution to meet some of the future energy needs of the world and is being heralded by engineers because of the following advantages:

Safe

The past nuclear mishaps at TMI and Chernobyl were because of human error and mechanical failure. They were due to the disruption of the active cooling mechanisms (i.e. pumps, valves, etc.) to the reactor cores. PBMR reactors have passive cooling mechanisms and have a negative temperature coefficient.

In other words, through natural radiation, convection and conduction, decay heat is removed from the reactor. Therefore, no melt-down scenario could physically occur. Each module reactor has a peak temperature that is well under the burn-up temperature of the fuel pebbles. The fuel pebbles themselves contain the radioactive fission products [L3]. Only a small amount of radioactive nuclides would be released in the event if a single fuel pebble should break. The fuel contained in the broken fuel element would still be divided among 15,000 particles, individually coated with ceramic materials [L3].

The helium used to cool the reactor is chemically inert. It doesn't react with any of the PBMR components and is non-combustionable[L3]. Operation of the plant involves little human intervention which will dramatically reduce the probability of error, even though the plant would remain stable after such an error.

The reactor does not have a radiation containment building but is housed by a protective structure to shield it from aircraft crashes and earthquakes. Radiation is contained with the pebble coatings.

Cost Competitive

Students at MIT compared energy costs to the capital and operational cost of a MPBR plant (which is very similar to the PMBR). The following results come from the 1992 National Energy Institute Study of Electricity: Natural Gas = 3.4 Cents/kwhr, Pebble Bed 3.3 Cents/kwhr [4]. Compared to the LWRs, the capital and operational costs are now competitive. Because of the small size of the reactor, main components can be manufactured remotely and shipped to the reactor build site. The ability to manufacture remotely reduces capital expenditures.

Proliferation Resistant

The PBMR is proliferation resistant since the uranium is located inside the TRISO fuel pebbles and it is diffcult to reprocess them. There is also only a small about of radioactive material in each fuel element to begin with.

DISADVANTAGES:

Some oppose the PBMR because they advocate that the design to have the following disadvantages:

No Containment Building

Since the PBMR reactor relies upon convection for cooling, no containment building that is characteristic of today's LWRs is present. If any radiation breach of the reactor were to occur, there would be no barrier to the public (except for the coatings on the pebbles).

Fuel Pebble Risky

The reliance of radiation containment is placed on the coatings of the TRISO fuel particles. This may be a little risky since there are so many fuel pebbles used in the reactor. Admittedly, there is at least 1 defect per particle produced [AL1]. Figure 6 (ref. [AL1]) shows an example of where cracks may occur in the fuel particle. Whether or not these defects affect the performance significantly is to be determined.

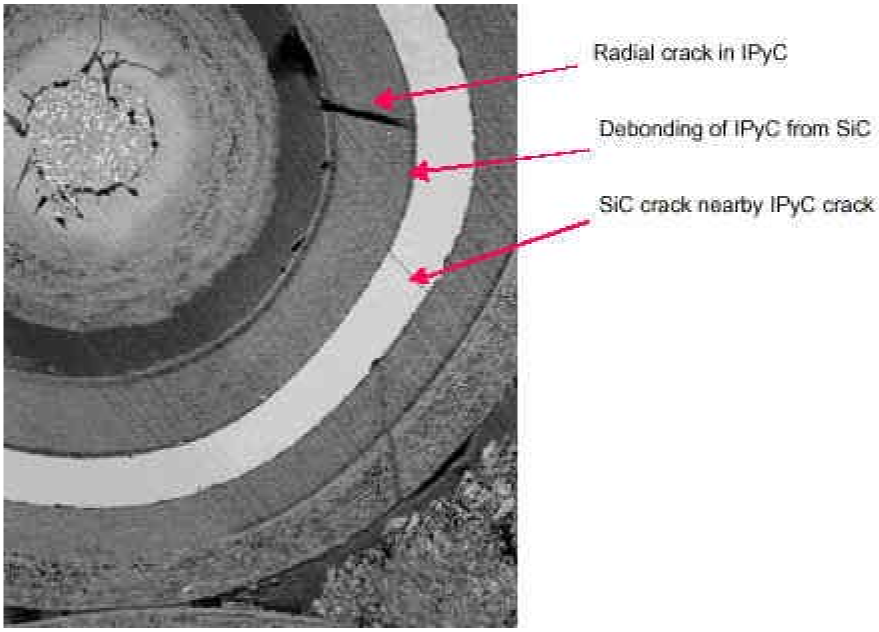

Figure 6: Photomicrograph of Defective Fuel Particle Cross-section (ref. [AL1])

Large Amount of Waste

Since one of the major safety features of the PBMR is a low power density core, a core of high volume is naturally needed. This consequently produces more waste to disppose. The volume of pebble bed fuel is about 10 times higher than an equivalent LWR of a megawatt basis [4].

DEVELOPMENTS:

As mentioned before China and Japan currently have operational pebble bed reactors.

The countries that are in the process of developing reactors and their expected years of operation are the following:

South Africa - 250 Mwth Pebble - 2003

Russia - 330 Mwe Pu Burner Prismatic - 2007 [L1]

The MPBR is jointly being researched by MIT and the Department of Energy's Idaho National Engineering and Evironmental Laboratory (INEEL) [AL3] .

REFERENCES:

[1] Yoshiaki Ichihara, *A Perspective on Nuclear Power Generation in the Future Electric Power Industry - For Nonspecialists in the Electric Power Related Industries*, in Proceedings of the IEEE, Vol.

89, No. 12, December 2001.

[2] Jenny Weil, *Pebble-Bed Design Returns*, in IEEE Spectrum, November 2001, pg. 37 - 40.

[3] H. L. Brey, *Historical Background and Future Development of the High Temperature Gas Cooled Reactor*, presented at Seminar on HTGR Application and Development, Institute of Nuclear Engineering Technology, Tsinghua University, March 19-21, 2001, Beijing China (found in [L2])

[4] Andrew C. Kadak, Ph.D., *The MIT Modular Pebble Bed Reactor Project*, March 19, 2001 (found in [L2])

LINKS:

Pro-PBMR sites:

[L1] http://web.mit.edu/pebble-bed - Link to Modular Pebble Bed Reactor, Department of Nuclear Engineering, M.I.T.

[L2] http://www.inet.tsinghua.edu.cn/english.htm - Link to Institute of Nuclear Energy Technology, Tsinghua University

[L3] http://www.pbmr.com - Link to PBMR website, hosted by British Nuclear Fuel and Exelon

[L4] http://www.ist.co.za/frames.asp?page=industrial/pbmr.asp - Link to PBMR manufacturer IST Industrial

Anti-PBMR sites:

[AL1] http://www.tmia.com/pebbles.html - Link to anti-PBMR article sponsored by Three Mile Island Alert

[AL2] http://www.nirs.org/factsheets/PBMRFactSheet.htm - Link to anti-PBMR article sponsored by Nuclear Information Resource Service

[AL3] http://www.ieer.org/comments/energy/chny-pbr.html - Link to anti-PBMR article sponsored by Institute for Energy and Environmental Research